2006 R&D 100 AWARDS ENTRY FORM

1 Submitting Organization

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AFFIRMATION: I affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product.

Submitter's signature: ____

2 Joint entry with: Not applicable.

3 Product name:

High-Output Coaxial-Target Neutron Generator

4 Briefly describe (25 words or less) what the entry is (balance, camera, nuclear assay, etc.)

A high yield, continuous beam neutron generator that uses no radioactive elements and gives about a thousandfold more neutron output than direct competitors now on the market. Applications in use or being actively developed include neutron-capture therapy for cancer; testing of advanced integrated circuits; ultrasensitive elemental analysis of medical samples; and explosives detection.

5 When was this product first marketed or available for order? (Must have been first available in 2005.)

As a national laboratory, Berkeley Lab does not manufacture articles for sale; rather, it invents, develops, and licenses technology. The technology was made available for license in 2005 and the first nonexclusive licensing agreement with Adelphi Technology, Inc. was executed in 2005.

6 Inventor or Principal Developer (List all developers from all companies)

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7 Product price

To be determined by each licensee.

8 Do you hold any patents or patents pending on this product?

We have filed patent application # 20,050,220,244 with the United States Patent and Trademark Office.

9 Describe your product's primary function as clearly as possible. What does it do? How does it do it? What theories, if any, are involved?

This specific item (which is part of a family of technologies based on similar core concepts) safely, easily, and dependably makes large amounts of neutrons.

Many useful and important functions can be performed by taking advantage of the way neutrons (heavy subatomic particles carrying no electric charge) penetrate and interact with matter. The feasibility and efficiency of these applications depend on the availability of large quantities of neutrons from a compact, inexpensive, user-friendly device. These applications are of great financial and societal importance; they include:

- Investigational therapy for difficult-to-treat brain cancers that strike thousands of people in the US and tens of thousands worldwide each year. A unit has been installed at the University of Turin for small-scale experimental treatments of these and certain other cancers of the liver and soft tissues.
- Ultrasensitive detection of certain elements in medical specimens, being explored with BioPal, Inc., of Worcester, Massachusetts, which applies neutron activation to products for drug discovery and drug-delivery verification.
- Screening of cargo for explosives that contain nitrogen, the subject of intensive discussions with government organizations and companies in the homeland-security sector.
- Industrial neutronics applications such as studying the effects of neutrons on flash-memory chips and microprocessors: work that two leading manufacturers have performed using our facilities.
- Inspection for hidden flaws in new and in-service products (e.g., in cooling pipes found in nuclear facilities). Adelphi Technologies, Inc., is pursuing this under our licensing agreement with them.

The High-Output Coaxial-Target Neutron Generator enables new applications, and vastly improves existing ones, by creating neutrons in amounts unrivaled by devices of comparable size, safety, and ease of use. Its thousandfold higher output, compared to directly comparable generators now available, translates directly into increases in speed or sensitivity of user applications.

Innovations Combine High Flux, Low Maintenance

The device produces neutrons in a deuterium-deuterium (D-D) fusion reaction that occurs when accelerated beams of ionized deuterium—a non-radioactive, non-toxic, heavier form of hydrogen—strike a target that also contains deuterium.

The Berkeley Lab team has developed an array of innovations to give this D-D technology high neutron output while keeping equipment lifetime long and avoiding the need to use radioactive tritium. The innovations include a plasma generator, driven by radiofrequency (RF) energy, that gives powerful, concentrated, high-purity output, as well as a coaxial geometry that puts a large target area into a small overall volume.

The Principles Behind a Thousandfold Neutron Output Improvement

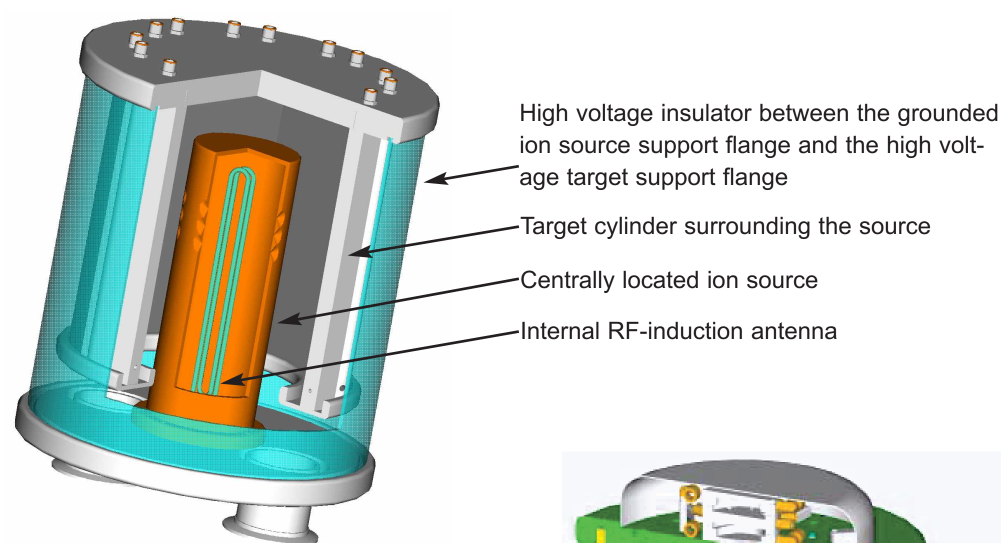
As Figure 1 shows, one of the key innovations is a concentric, cylindrical ("coaxial") geometry in which a cylinder-shaped RF-driven plasma generator (ion source) is surrounded by a cylindrical target. At the heart of the plasma generator is another important feature: an innovative antenna design. The antenna is a hollow, water-cooled quartz tube in which an RF conductor is placed (Figure 2). The electromagnetic field from RF induction gives energy to the electrons in the discharge volume. Electron-neutral collisions form an ionized gas, or plasma. The RF induction is a powerful way of ionizing the neutral gas in the discharge volume. The resulting plasma density is directly proportional to the RF discharge power.

As shown in Figure 3, high plasma density also produces about a 90% atomic-species purity (that is, D^+ rather than D_2^+ ions), which is far better than the 20% typically achieved in the Penning-type ion sources found in most neutron generators. The higher atomic-species fraction results in higher neutron flux because the D_2^+ ions are twice as heavy and therefore are not accelerated to the full speed needed for efficient fusion. At typical 100-kV acceleration voltages, the end result is about a sevenfold advantage in neutron-production efficiency.

This RF induction scheme, with its power, simplicity, and durability, is one of the key features of the LBNL neutron generators. These ion sources can produce current density (and consequently extractable ion current and ultimately neutron output) orders of magnitude higher than more conventional means, like the Penning discharge scheme used by most existing sources. This is how the Berkeley Lab technology achieves such high neutron flux without using radioactive tritium, which existing/competing technologies need in order to achieve similar flux. Because the D-D reaction has a much smaller cross section for neutron production than does D-T, achieving such flux without the drawbacks of tritium is a tremendous advantage to the user.

Combining High Output With Predictability, Long Life, and Easy Maintenance

The Berkeley Lab neutron generator uses an existing concept called a “beam loaded” target. During the first few minutes of operation, incoming deuterium ions implant themselves in the target. Subsequent deuterium ions in the beam strike and fuse with those in the target, resulting in emission of fusion neutrons. This “beam loading” occurs continuously during operation, ensuring a very stable neutron yield because the amount of deuterium in the target becomes steady, maintained in equilibrium by the beam itself.



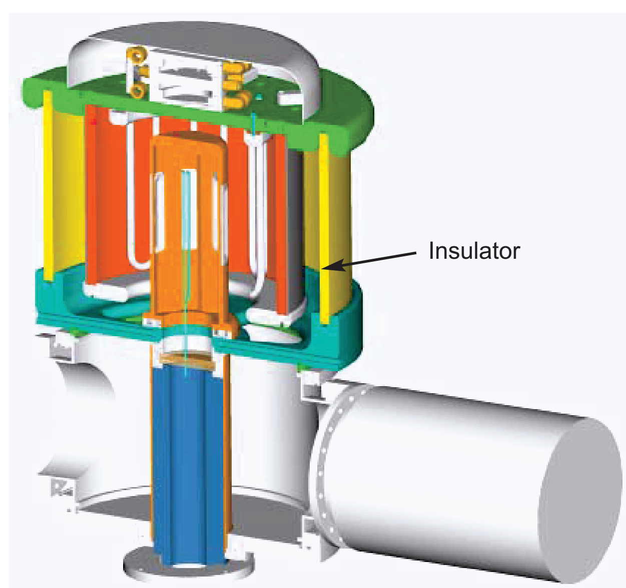


Figure 1 Top: Main components of the Berkeley Lab coaxial–target neutron generator. Bottom: The complete unit installed at Turin. The neutrons are principally emitted radially through the insulator shown in yellow on these computer-aided-design renderings.

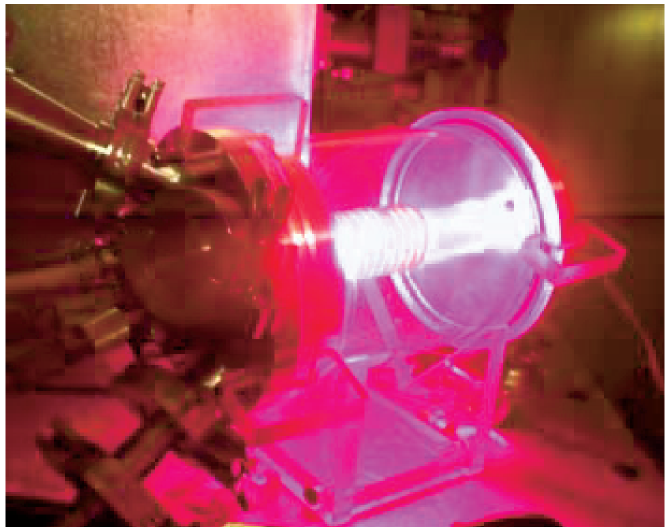


Figure 2 Testing of an ion source that has an external antenna illustrates the RF antenna coil. The Berkeley Lab coaxial-target neutron source uses an internal antenna of similar design. The antenna is simple, and based on extensive experience with ion sources and with our test-stand and early-adopter neutron sources, we project that it will be long-lived as well.

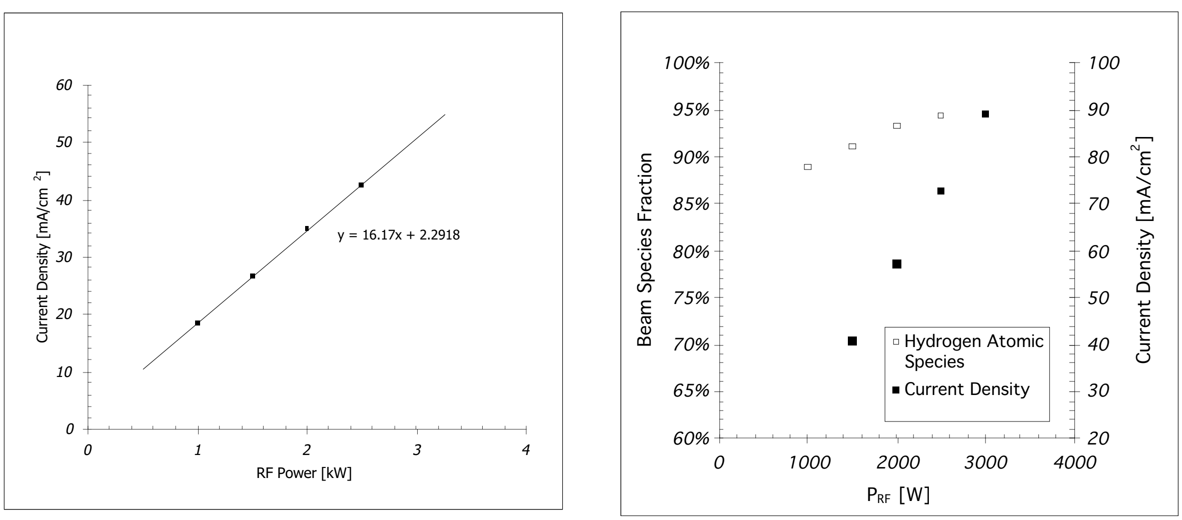


Figure 3 Current density as a function of radiofrequency power for the neutron source installed at Turin for neutron capture therapy research. Right: current density and ionic species fraction for a similar Berkeley Lab ion source that operated at about double the power of the Turin model. High current density and high purity of ion species both translate directly into high neutron yield. Together with the coaxial configuration, these are the key reasons why the Berkeley Lab neutron generator produces such high neutron flux.

LBNL and other laboratories have years of experience with these ion sources in a variety of applications. Antenna lifetimes in excess of 1000 hours have been demonstrated thus far with this glass-coated antenna with no indications of wear or failure. The coaxial geometry greatly increases the available target area, allowing for efficient cooling despite the intense ion beams. Since radioactive tritium, pre-loaded targets, and ultrahigh vacuum components are not involved, maintenance of generator components, when needed, can be done at the site of operations.

High Output Translates Directly Into Advantages to the User

The highest-output neutron generator we have developed to date—the one installed at the Neutron Capture Therapy facility in Turin—is designed to produce 10^{11} neutrons per second in sustained, continuous operation. That is an advantage of three orders of magnitude over the highest output D-D competitor, marketed through Thermo Electron Inc., with its advertised neutron yield of 10^8 n/s. The high flux of neutrons is of direct benefit to user applications; it translates directly into faster treatments and higher throughput, compared to lower-flux sources of neutrons.

In neutron activation analysis, the samples are activated by fast or thermal neutrons and subsequently analyzed by the characteristic gamma radiation of each of the sample elements. This is a sensitive way of characterizing elemental composition of samples in biomedical, homeland-security, and materials-science applications. The analysis becomes faster and more sensitive when the neutron flux is higher.

D-D neutron generators offer certain clear advantages when compared to the D-T generators that are otherwise needed to get comparable flux. First, there is no need for radioactive tritium. Because of the hazards of tritium, using it would require a special license and also trigger the need for ultrahigh vacuum and a hermetically-sealed source, all of which would drive up cost and complicate maintenance. The user of our D-D source can readily transport, operate and maintain the unit in the field with confidence of easy operation and continued long service. Second, the lower-energy neutrons (D-D neutron energy peaks at 2.45 MeV) cause less unwanted activation of surrounding materials than the 14.1-MeV neutrons of the D-T reaction. Third, the lower initial neutron energy means that the moderator structure, which delivers the ultimately desired neutron energy, can be smaller and more efficient.

10A List your product's competitors by manufacturer, brand name and model number.

The most direct and significant competitors are commercially available neutron tubes based on a Penning-type cold-cathode ion source and a single-aperture electrostatic extractor. Typical D-D neutron tubes representative of prominent manufacturers include:

EADS Sodern Soditron Genie-16.

Thermo Electron Corporation A-325.

FirstPoint Scientific LENG.

Thermo Electron Corporation HY-LENG.

10B Competitive Matrix

Table 1 compares the High-Output Coaxial Target Neutron Generator to typical Penning-type D-D neutron generators. Also compared is a representative D-T source meant for high-flux stationary installations. Note that the D-D sources produce 10^6 to 10^8 neutrons per second, depending on duty factor—favorably comparable to the D-T source, and at least a factor of 1000 and in some cases a factor of 10^5 below the 10^{11} neutrons per second (continuous) of our highest-output source.

Table 1 Competitive matrix compares the LBNL high output coaxial target neutron generator to commercially available alternatives.

	Berkeley Lab High-Output Coaxial Source	Soditron Genie-16	Thermo Electron A-325	FirstPoint LENG	Thermo Electron HY-LENG	Thermo Electron A-711 (D-T)	Competitive Advantage
D-D neutron flux [n/s]	10^{11}	$2x10^6$	$5x10^8$ (50% duty factor)	10^8	10^8	$2x10^{10}$ D-T	Faster and/or more thorough results
Ultrahigh vacuum required?	No	Yes	Yes	Yes	Yes	Yes	Cost and ease of use
Radioactive material required?	No	No	No	No	No	Yes	High flux without tritium is highly desirable
Lifetime	Thousands of hours at max flux (project-ed); hundreds in ongoing observations	Hundreds of hours	1500 hours	Hundreds of hours	3000 hours	Hundreds of hours at max flux (2000 at $5x10^9$)	High operational availability; low overall cost of ownership
Pulse structure and tuning	Developmental; see answer 11B	10 Hz-20 kHz	>5 µs; 100 Hz-20 kHz; continuous	10-40 µs; 10-1000 Hz	continuous only	continuous only	Relative ease of access to entire range of possibilities for different applications
Neutron-seconds per dollar[1]	$5x10^5$	20	$5x10^4$	$1x10^4$	$1x10^4$	$5x10^4$	1000x higher flux puts it in unprecedented price/performance category

[1] The calculations were based on the rough price estimate (source plus power supply) of $100k for Penning-type sources and $200k for sources based on our technology. However, the overwhelmingly dominant term is the tremendous flux advantage of this technology. Not considered here is the fact that using a D-T source in the quest for higher flux would also increase the size and cost of the moderator, if the ultimately desired neutron energy for the application is at or below the D-D spectrum.

10C Describe how your product improves upon competitive products or technologies.

The Berkeley Lab High-Output Coaxial-Target Neutron Source has two classes* of competitors for field or small-laboratory use in security and R&D. They are isotopic sources (based on a sample of a radioactive substance that emits neutrons, usually ^{252}Cf at 2.3 MeV) and conventional (Penning-type) neutron generators.

Advantages Over Existing Neutron Tubes

The most significant advantage is the high neutron output. The improvement as seen by the user—higher throughput, for instance, or more-sensitive analysis—is proportional. Another significant advantage is the use of only deuterium gas—not radioactive tritium with its special licensing requirements, environment, safety, and health hazards, and higher costs. Pure deuterium operation makes maintenance easier as well because the Berkeley Lab neutron generator can be disassembled and maintained without risk of tritium contamination of personnel and surroundings.

For applications requiring thermal or epithermal energy neutrons, starting with the lower-energy neutrons from the D-D reaction also lets the moderator be smaller and simpler.

Advantages Over Isotopic Sources

The Berkeley Lab neutron generator is not only intrinsically safer and lower in regulatory concerns than radioactive sources, but unlike them, can be turned on and off. Isotopic sources have another particular disadvantage in homeland security where they might be broken and scattered by the detonation of explosives—in fact, they might be considered security hazards in their own right, if stolen, as potential material for a "dirty bomb."

High Flux and Associated Advantages Are Seen by Users

The high neutron output of the Berkeley Lab source enables it to compete with cyclotrons or linear-accelerator-based neutron sources because it is more compact and cheaper to purchase and operate. A product based on this technology might be

* Two other ways of producing neutrons—large accelerator complexes (usually based on an ion source feeding one or more linacs and thence circular accelerators and a production target) and nuclear reactors—are not competitors in the small-laboratory and field/portable markets. A low-energy accelerator-based source incorporating a radiofrequency quadrupole linac has been deployed as part of security systems (e.g., one made available by Science Applications International Corp. for airport use) but has never become a major commercial presence due to cost, operational complexity, and size.

desk-sized and priced in the low hundreds of thousands of dollars, rather than truck-sized and priced in the millions.

The higher neutron yield also translates into higher throughput for baggage and cargo screening and other security-related applications based on thermal neutron activation analysis. These applications benefit from the small size and low cost of the generator, while the high flux minimizes the economic impact of security by enabling the screening system to effectively process more items faster.

We expect that operational experience in the field will demonstrate two additional improvements: simplicity (in both construction and operation) and reliability.

The setup and operation procedure (vacuum pumping, deuterium gas flow, RF power, and high voltage) can be largely automated. These devices should not need highly trained technicians for routine operation.

11A Describe the principal applications of this product.

Principal applications include:

- Research into neutron capture therapy that aims for clinical trials and thence approved therapy of certain brain, liver, and other difficult-to-treat tumors.[2] The co-axial neutron generator for NCT studies was delivered to the University of Turin, Italy in November 2004 (Figure 4).
- Neutron activation analysis of medical samples. This application is being actively developed by a private-sector collaborator, BioPal, Inc.
- Thermal neutron activation analysis for homeland-security and force-protection applications in explosives detection. These applications are the subject of proposals currently under consideration.
- R&D on neutron effects in semiconductors. One of the leading manufacturers of flash memory units is using our test stand to study the effects of neutrons upon high-density/small-feature-size flash memories. (Neutrons produced in the atmosphere by cosmic rays can change the memory state of a bit, especially in highly miniaturized chips that use natural boron as a doping agent.) A manufacturer of microprocessors has performed investigations in this area as well, using our technology and facilities.

[2] The principal target of neutron capture therapy research is Glioblastoma multiforme, described as “the most common and aggressive of the primary brain tumors” and striking 2 to 3 of every 100,000 people worldwide each year (http://www.emedicine.com/NEURO/topic147.htm). The researchers involved with Turin are also looking at NCT as a treatment for certain liver tumors and other near-surface soft-tissue cancers. Besides a compact, safe, and inexpensive neutron source (research to date has primarily used nuclear reactors), NCT also depends upon neutron-absorbing drugs that preferentially accumulate in the cancerous tissue. This aspect is being explored by others.

- Neutron radiography for detecting hidden flaws in metal items in service—for example, pipes in nuclear reactor facilities. This application led a private-sector collaborator, Adelphi Technology, Inc., to license the technology.

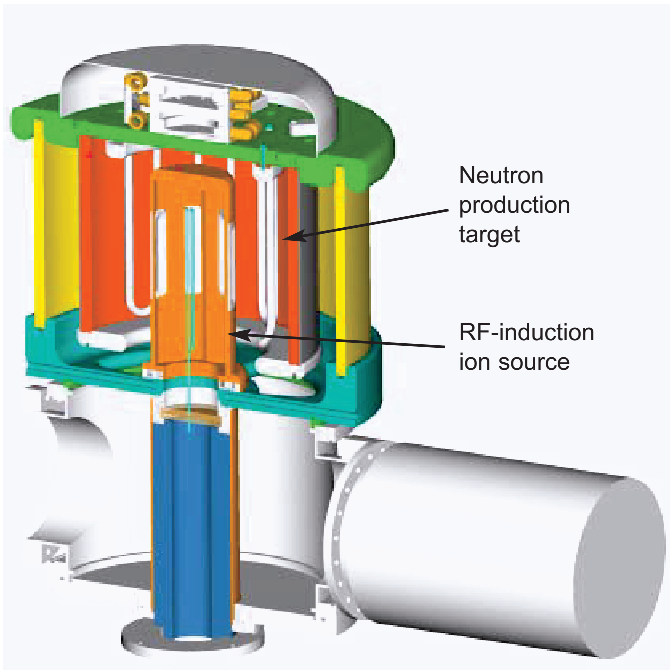


Figure 4 This D-D coaxial neutron generator, designed for an output of 10^{11} n/s, was delivered to the hospital/university consortium EUROSIA in November 2004, in Turin, Italy. On the right, the generator is shown being set up for testing in a neutron generator test stand at LBNL.

11B List all other applications for which your product can now be used.

In its present version, the High-Output Coaxial-Target Neutron Generator provides continuous output and employs the D-D fusion reaction. However, pulsed versions based on these concepts and technologies could be engineered by gating the RF power, the high-voltage beam extractor, or both. Also, versions that use tritium could be engineered, giving an estimated 100x more output than the existing design.

One application for a pulsed source of this nature is another aspect of homeland security: screening for special nuclear materials (SNM) such as plutonium or highly enriched uranium. This type of material presents an exceptional challenge because terrorists might not be smuggling items that are shaped like the internal parts of weapons, nor transporting large quantities in one shipment. Security screeners must have a way to detect small amounts, in most any shape, disguised as innocuous items and concealed amid other cargo. A high-output neutron source with fast, sharp pulse falloff could be used for "neutron die-away" detection techniques, yielding a valuable tool for efficiently searching incoming vehicles and cargo without impeding commerce. Based on our extensive ion-source experience and previous testing, we find it reasonable to suggest that pulse structures much faster than the milliseconds that are characteristic of Penning-type sources could be achieved by variants of this technology.

For applications where the need for higher-energy neutrons or a desire for still-higher flux dictate the use of the D-T reaction, a continuous or pulsed version suitable for use with tritium could be engineered.

Another intriguing prospect is a T-T source. The T-T fusion reaction gives off neutrons across an exceptionally broad energy distribution: from 1 to 9 MeV. The breadth of the spectrum, the higher energies, and the possibility of pulsing the output by means of either RF or HV has led us to investigate T-T versions of the basic technology. We are developing configurations suitable for use as line sources or point sources that also have a cylindrical geometry. Their applications would be Fast Neutron Transmission Spectroscopy (FNTS) or Pulsed Fast Neutron Transmission Spectroscopy (PFNTS).

In its present continuous-output, D-D version and in these further developments, the High-Output Coaxial Plasma Neutron Source could greatly expand access to neutron applications for R&D and for education of future scientists and engineers. The neutron output does not compare in flux or geometrical brightness to that of fission reactors or large accelerator-driven spallation sources. However, it is much more adaptable to the university and small-laboratory environment while providing orders of magnitude higher neutron output than existing, commercially available neutron generators.

12 Summary. State in layman's terms why you feel your product should receive an R&D 100 Award. Why is it important to have this product? What benefits will it provide?

The High-Output Coaxial-Target Neutron Source benefits users in three broad areas: cancer therapy, industrial applications, and homeland security.

Several thousand people in the US alone each year—several tens of thousands worldwide—are stricken by Glioblastoma multiforme and other cancers that are difficult to treat by conventional means. The charter application for the High-Output Coaxial Target Neutron Source is neutron capture therapy. In this experimental form of treatment, the patient is given drugs that preferentially concentrate in the cancer rather than in healthy tissue, and contain elements that are unusually effective at capturing neutrons. A dose of neutrons is then applied to the affected area. Enjoying renewed interest (especially in Europe) with a new generation of neutron-capturing pharmaceuticals, the practicality of this form of treatment depends on a small, safe, and low-cost source of a high flux of neutrons. Our technology is well suited to the hospital environment compared to nuclear reactors or sizable linac-based neutron sources, and provides neutrons that can easily be moderated into the desired epithermal energy range.

Industrial applications can also benefit from this technology. Neutron irradiation tests are currently done by a major flash memory manufacturer in our neutron facility, utilizing the high neutron output of the coaxial neutron generator. Neutron activation analysis of medical samples is among the other high-feasibility uses already being explored in cooperation with the private sector.

The Berkeley Lab technology's safety, reliability, user-friendly operation, and high neutron output, combined with the potential for further development leading to pulsed operation and/or the use of tritium, also give it great potential in national security and related endeavors. Among the especially urgent scenarios are protection of intrinsically vulnerable systems; detection of highly concealed threats such as explosive vests, car bombs, and leave-behind charges; and screening for nuclear weapons and their constituent materials in cargo.

The risk to high-profile targets can be greatly mitigated by systems that sensitively detect nitrogenous explosives without an unacceptable rate of false alarms. The even more urgent need to check for strategic nuclear materials could benefit from the same advantages.

In short, the High-Output Coaxial-Target Neutron Source can accomplish most of the things that competing technologies can, while providing speed or sensitivity up to a thousand times better with only perhaps a twofold increase of whole-system price. It is safer than D-T sources, low in maintenance requirements, and relatively easy to set up and use. Thus it holds the promise of opening applications that were physically or financially unfeasible, in addition to improving existing applications.

ORGANIZATION DATA

13 Contact person to handle all arrangements on exhibits, banquet, and publicity.

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Appendix
List of Attachments
2005 R&D 100 Awards
High-Output Coaxial-Target Neutron Source (Berkeley Lab)

Appendix A. Letters of Support

Appendix B. Press Coverage

"*Neutroni per battere il cancro*" (literally "neutrons to strike cancer"), La Repubblica (Italy), 11 January 2005.

Appendix C. Select Publications

J. Reijonen, "Compact neutron generators for medical, homeland security, and planetary exploration" (invited talk), in Proceedings of the 2005 Particle Accelerator Conference (Knoxville, Tennessee, USA, May 16-20, 2005), IEEE publication 0-7803-8859-3/05.

J. Reijonen, F. Gicquel, S.K. Hahto, M. King, T.P. Lou, and K.-N. Leung, "D-D neutron generator development at LBNL," in Proceedings of the 8th International Conference on Applications of Nuclear Techniques (Crete, Greece), Applied Radiation and Isotopes 63 (2005), pp. 757–763.

J. Reijonen, K.-N. Leung, R.B. Firestone, J.A. English, D.L. Perry, A. Smith, F. Gicquel, M. Sun, H. Koivunoro, T.-P. Lou, B. Bandong, G. Garabedian, Zs. Revay, L. Szentmiklosi, and G. Molnar, "First PGAA and NAA experimental results from a compact high intensity D–D neutron generator," letter in Nuclear Instruments and Methods in Physics Research A 522 (2004), pp. 598–602.

2005 R&D 100 Awards
ENTRY—High-Output Coaxial-Target Neutron Source
(Berkeley Lab)

Appendix A:

Letters of Support

BioPal, Inc.

2005 R&D 100 Awards
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